SIMULTANEOUS POWER GENERATION AND WASTEWATER TREATMENT USING MICROBIAL FUEL CELL

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LIST OF ABBREVIATIONS

B

BOD	Biochemical Oxygen Demand

C

CE	Coulumbic Efficiency
CO	Carbon Monoxide
COD	Chemical Oxygen Demand

D

DMRB	Dissimilatory Metal-Reducing Bacteria
DOE	Department of Environment Malaysia

E

EAB	Electrochemically Active Bacteria

G

GAC	Granular Activated Carbon

M

MFC	Microbial Fuel Cell

O

OCV Open Circuit Potential

P

PACF Polyacrylonitrile Carbon Felt

PD Power Density

PEM Proton Exchange Membrane

POME Palm Oil Mill Effluent

S

SCMFC Single Chamber Microbial Fuel Cell

SPW Starch Processing Wastewater

T

TS Total Solid

TSS Total Suspended Solid

LIST OF SYMBOLS

Symbol	Description	MKS Units
A	Area of Electrode	m^2
C	Concentration	mol/L or M
D	Diameter	Mm
d	Depth	Cm
F	Faraday's Constant	C/mol e^-
I	Current	A
I_{max}	Maximum Current	A
L	Thickness/Length	mm
P	Power	W
q	Electrical Charge	C
R	Resistance	Ω
s	Conductivity	mS/cm
T	Temperature	℃
t	Time	Hr
V	Voltage	V
V	Volume	mL
v	Working Volume of Anode	m^3
V_{An}	Volume of Liquid in Anode Compartment	mL
V_{max}	Maximum Voltage	V
X	Concentration of Biomass	mg/L
Δ_{COD}	Change in COD Concentration	mg/L

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ABSTRAK

Efluen kilang minyak sawit (POME) merupakan salah satu pencemar di Malaysia. Konvensional aerobik dan anaerobik rawatan air sisa memerlukan lebih banyak tenaga untuk beroperasi. Dalam konteks ini, rawatan air sisa menggunakan Microbial Fuel Cell seolah-olah menjadi teknologi yang menjanjikan kerana ia mengurangkan keperluan tenaga operasi dan menunjukkan rawatan yang berkesan juga. Kajian ini tertumpu kepada penjanaan kuasa serentak dan rawatan air sisa dengan menggunakan MFC. Objektif kajian ini adalah untuk mengkaji prestasi MFC dengan menggunakan karbon Polyacrylonitrile sebagai elektrod dan untuk mengkaji kesan luas permukaaan elektrod pada kecekapan coulombic dan kecekapan penyikiran Chemical Oxygen Demand (COD) untuk MFC. POME telah digunakan untuk menuai tenaga dan mengurangkan COD dari POME kompleks. Saiz yang berbeza untuk PACF elektrod telah digunakan sebagai elektrod untuk semua eksperimen. Cara penggumpulan data adalah melalui memerhati dan merekodkan voltan, arus dan kuasa yang dihasilkan oleh MFC. Hasil kajian telah dianalisis untuk mendapatkan ketumpatan kuasa yang optimum, kecekapan coulumbic dan kecekapan penyingkiran COD. Ketumpatan kuasa, ketumpatan arus dan kecekapan coulombic MFC dengan POME telah dikira. Membandingkan keputusan yang diperolehi dan dikira, MFC dengan luas permukaan ($34.79cm^2$) menunjukkan nilai tertinggi bagi ketumpatan kuasa maksimum kira-kira 76,2133 mW/m2, kecekapan coulumbic sebanyak 0.9561% dan kecekapan penyingkiran COD sebanyak 45.6%.

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ABSTRACT

Palm Oil Mill Effluent (POME) is one of the major pollutants in Malaysia. Conventional aerobic and anaerobic treatment of wastewater needs more energy to operate it. In this context, treatment of wastewater using Microbial Fuel Cell seems to be promising technology because it reduces operational energy requirement and shows efficient treatment too. This research focused on simultaneous power generation and wastewater treatment by using MFC. The objectives of the study are to study the performance of MFC using Polyacrylonitrile carbon felt (PACF) as electrode and to study the effect of surface area of electrode on coulombic efficiency and Chemcial Oxygen Demand (COD) removal efficiency of MFC. POME was used to harvest energy and reduce COD from complex POME. Different size of PACF was used as electrode for all the experiments. The data collection mode was through observing and recording the voltage, current and power produced by the MFC. The findings were analyzed to obtain optimum power density, coulumbic efficiency and Chemical Oxygen Demand (COD) removal efficiency. Power density, current density and coulombic efficiency of MFC with POME were calculated. Comparing the results obtained and calculated, MFC with PACF surface area (34.79cm^2) showed the highest value for maximum power density of about 76.2133 mW/m^2, coulumbic effiency of 0.9561% and COD removal efficiency of 45.6%.

CHAPTER 1

INTRODUCTION

Microbial fuel cells (MFCs) have emerged in recent years as a promising yet challenging technology. In a MFC, microorganisms interact with electrodes using electrons, which are either removed or supplied through an electrical circuit. MFC is considered to be a promising sustainable technology to meet increasing energy needs, especially using wastewaters as substrates, which can generate electricity and accomplish wastewater treatment simultaneously, thus may offset the operational costs of wastewater treatment plant. Bacteria can be used in MFCs to generate electricity while accomplishing the biodegradation of organic matters or wastes.

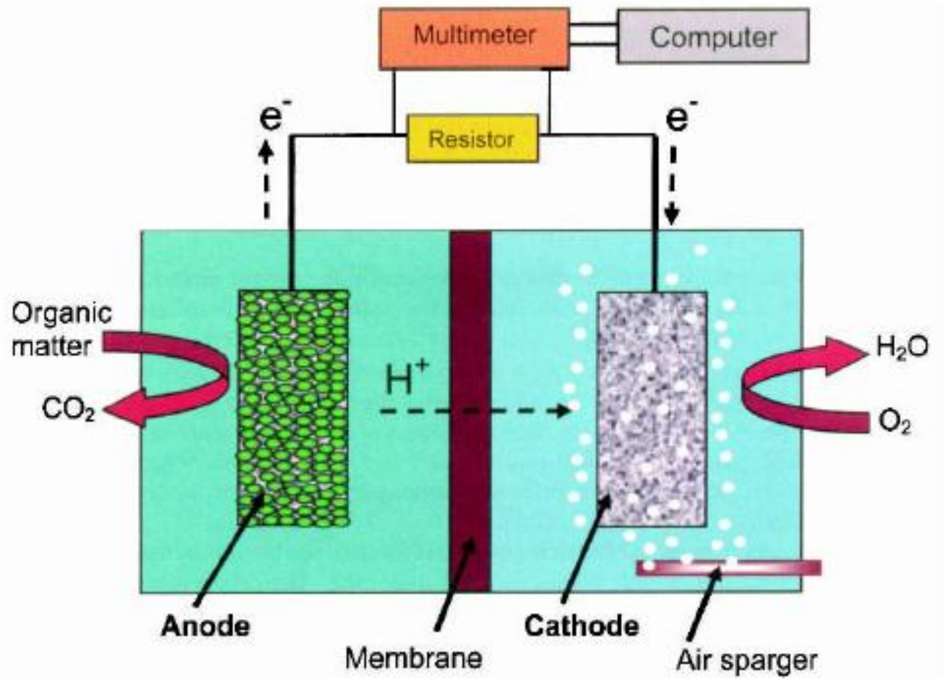

Figure 1.1 Graphical Representation of Microbial Fuel Cells (Logan, B.E. 2008.Microbial fuel cells)

Microbes in the anodic chamber of an MFC oxidize added substrates and generate electrons and protons in the process. Carbon dioxide is produced as an oxidation product. However, there is no net carbon emission because the carbon dioxide in the renewable biomass originally comes from the atmosphere in the photosynthesis process. Unlike in a direct combustion process, the electrons are absorbed by the anode and are transported to the cathode through an external circuit. After crossing a Proton Exchange Membrane (PEM) or a salt bridge, the protons enter the cathodic chamber where they combine with oxygen to form water. Microbes in the anodic chamber extract electrons and protons in the dissimilative process of oxidizing organic substrates. Electric current generation is made possible by keeping microbes separated from oxygen or any other end terminal acceptor other than the anode and this requires an anaerobic anodic chamber.

Typical electrode reactions are shown in Equation (1.1) and Equation (1.2) using acetate as an example substrate.

Anodic reaction: $CH3COO^- + 2H2O \longrightarrow$microbes $2CO_2 + 7H^+ + 8e^-$ (1.1)

Cathodicreaction : $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$ (1.2)

The overall reaction is the break-down of the substrate to carbon dioxide and water with a concomitant production of electricity as a by-product. Based on the electrode reaction pair above, an MFC bioreactor can generate electricity from the electron flow from the anode to cathode in the external circuit.

The first experimental evidence of bioelectricity was found in the late eighteenth century by Luigi Galvani, who observed electric response by connecting frog legs to a metallic conductor. To further explore the potential of bioelectricity, Michael C. Potter built the first MFC in 1911. In the 1980s, British researcher H. Peter Bennetto succeeded in extracting electric power from MFCs by employing pure cultures of bacteria to catalyze the oxidation of organics and utilizing artificial electron mediators to facilitate electron transfer in the anode. The number of MFCs applied to the biological treatment of wastewater increase greatly during the 1990s, especially after Logan and other researchers developed new MFCs using municipal or industrial wastewater as the substrate which greatly facilitated the technology.

At present, however, one of the bottleneck problems for the application of this methodology is the low output of power. Principally, the output power depends on the rate of substrate degradation, the rate of electron transfer from the bacteria to the anode, the circuit resistance, the proton mass transfer in the liquid, the performance of the electrode and the external operating conditions and so on.

Electrode is the key component in deciding the performance and cost of MFC. Electrode design is the greatest challenge in making MFCs a cost-effective and scalable technology. Recently, interest in the electrode material and its configuration has steadily increased in studies for MFCs. Over the past decade, a variety of electrodes have been extensively explored for MFCs. These electrodes can be classified into two main groups, bio-electrodes (including anode and biocathode) and chemical-electrodes (more specifically, air-cathode and aqueous air-cathode), according to whether or not bacteria is used as a catalyst.

Different electrode materials vary in their physical and chemical properties (e.g., surface area, electric conductivity, and chemical stability), thus, they also vary in their impact on microbial attachment, electron transfer, electrode resistance and the rate of electrode surface reaction. Therefore, it is of great significance to select and develop suitable electrode materials to optimize and promote the performance of MFCs. Moreover, as a main component, the electrode materials determine the price of MFCs and thus influence the wastewater treatment cost. Therefore, this field has attracted ever-increasing interest and lots of efforts related to electrode preparations and designs have been made.

The attractiveness of this novel technology is related to the wide range of potential applications, including the possibility of achieving energy recovery from wastewaters. In addition MFCs have been considered for hydrogen production, sulphide removal, and as biosensors for organic content in wastewaters. Many MFC devices utilizing specific axenic cultures have been developed, however, MFCs operated with mixed cultures show higher resistance against process disturbance, larger substrate versatility and also higher power output.

Since the first application of the two chamber design, the configuration of MFCs has been continuously optimized. Moreover, improved electrode materials and better understanding of bacterial community involved in the electrochemical reactions, have led to ever increasing performance.

The maximum current (I_{max}) generated with MFCs is still very low, being only of 0.1A, and the average power density of MFCs is about $40Wm^{-3}$, when operated in batch mode and fed with a synthetic wastewater. The major obstacles for practical applications of MFCs in a wastewater treatment plant concerns difficulties mainly in the scaling-up process and the very high capital costs.

1.1 Background of Research

The use of fossil fuels, especially oil and gas, in recent years has accelerated and this triggers a global energy crisis. Renewable bio energy is viewed as one of the ways to alleviate the current global warming crisis.

It is undeniable that energy cannot be created nor destroyed. It can only convert from one form to another, for instance Microbial Fuel Cells used substrates in wastewater to generate electricity and simultaneously the wastewater is being treated, which means the energy is converted from chemical energy to electrical energy. While the current technology is promising, none of the processes can fully extract all the energy available in wastewater. Therefore, new development and improvement of technologies are necessary to take advantage of the maximum energy available in sewage and sludge.

Significant advancements in increasing the current densities of microbial fuel cells have been made recently by modifying fuel cell architecture and materials while treating the microorganisms as a ‘black box’. Substantial improvements will be required before other commonly projected uses of microbial fuel cells, such as large-scale conversion of organic wastes and biomass to electricity, or powering vehicles, mobile electronic devices, or households with suitably scaled microbial fuel cells will be possible. Additional potential engineering modifications seem promising.

The anode material and its configuration represent an important parameter in a MFC, as it influences the development of the microbial community involved in the electrochemical bio-reactions. The study tries to evaluate MFC with high anode surface area, achieved by using polyacrylonitrile carbon felt (PACF). The performance of the MFC with the PACF anode configuration was studied using a mixed microorganism culture from real wastewaters in batch and continuous mode operation.

1.2 Problem Statement

Types of electrode material can be one of the factors that affect the performance of MFC. For all the types of electrodes, their base materials must generally be of good conduction, good chemical stability, high mechanical strength, and low cost. Besides the types of electrode material, the surface area of the electrode is also considered as an important parameter in determining the performance of MFC. There is an issue arises, by increasing the surface area of electrode, the coulombic efficiency of MFC will be increased or not?

1.3 Research Objective

1. To study the performance of MFC using Polyacrylonitrile carbon felt (PACF) as electrode.
2. To study the effect of surface area of electrode on Coulombic Efficiency and COD Removal Efficiency of MFC.

`1.4 Scope of the Research Work

- The anaerobic sludge and raw Palm Oil Mill Effluent (POME) that collected from the Neram Felda Palm Oil Industry are used in MFC for the simultaneous treatment of POME as well as to generate electricity.
- Various surface areas of PACF are used in anode and cathode compartments to determine the effect of electrode surface area on the performance of MFC.
- Optimized surface area of electrode is determined through observing the maximum current and power density produced by the MFC.
- How surface area of electrode affects Coulombic Efficiency is calculated using Chemical Oxygen Demand (COD) removal and current generation data of PACF with different surface areas.

1.5 Significance of the Research

This research will be a significant endeavour in solving energy crisis in a country by reducing the dependence on the fossil fuel to generate energy. Besides, the problem of wastewater can also be solved because, the organic waste in the wastewater will be eventually consumed and converted into electric energy by microorganisms that grow and exist in the wastewater.

CHAPTER 2

LITERATURE REVIEW

2.1 Palm Oil Mill Effluent (POME)

Palm Oil Mill Effluent (POME) is a thick brownish liquid that contains high amount of total solids (40,500 mg/L), oil and grease (4000 mg/L), Chemical Oxygen Demand (COD) (50,000 mg/L), and Biochemical Oxygen Demand (BOD) (25,000 mg/L). This highly polluting effluent is becoming a major problem to environment as if it not being treated well before discharged based on standard limit for effluent discharged. Normally, POME is treated by collecting the samples from mixing ponds which act as activated sludge and being analyze using water analyzer method to obtain parameters such as BOD, COD, suspended solid, turbidity and pH (Hazlan, 2006).

2.2 Inoculum

The majority of modern microbial fuel cells rely on mixed bacterial cultures, usually sampled from natural environments like from soil or sewage sludge. These cultures are abundantly available in our environment, they consist of wide range of substrates – ranging from simple organic acids (Liu et al., 2005), to carbohydrates including complex carbohydrates like starch and cellulose, (NieBen et al., 2006; Rismani-Yazdi et al., 2007) and even to proteins (Heilmann and Logan, 2006).

2.2.1 Electrochemically Active Bacteria

According to Chang et al., 2006, Electrochemically active bacteria (EAB) is defined as bacteria that possess the ability to transfer electrons from oxidized fuel (substrate) to a working electrode without mediators, making it possible to establish mediator-less MFCs. Dissimilatory metal-reducing bacteria (DMRB), which are capable of the reduction of solid metal oxides, are known EAB species, including *Geobacter*and *Shewanella* spp. It was shown that the anode electrode in MFCs served as the electron acceptor for growth and metabolism of EAB, which are capable of current production in the absence of a mediator.

2.2.2 Substrates of Microbial Fuel Cell

There are many organic substrates that can be the possible energy sources to generate electricity using MFC. These substrates range from carbohydrates (glucose, sucrose, and etc.), volatile fatty acid (acetate, formate, and etc.), alcohols (methanol and ethanol), amino acids, proteins and even inorganic components like sulphides (Cheng et al., 2007, Clauwaert et al., 2008c, He et al., 2005, Heilmann and Logan, 2006, Ishii et al., 2008, Liu et al., 2005b, Logan et al., 2005, Min and Logan, 2004, Rabaey et al., 2003, Rabaey et al., 2006). Due to the inertness towards alternative microbial conversions (fermentation and methanogenesis) at room temperature of acetate, it is considered as the commonly used substrate in MFCs. This results in high coulombic efficiencies of up to 98% (Rabaey et al., 2005b) and high power outputs of up to 115 $W.m^3$ (Cheng and Logan, 2007) for mixed anodophilic cultures.

2.2.2.1 Synthetic Wastewater

Synthetic or chemical wastewater with well-defined composition is also used by several researchers as it is easy to control in terms of loading strength, pH and conductivity. Venkata Mohan et al. (2008a,b) have used synthetic wastewater at different loading rates in similar MFC configurations to achieve variable performances. Several media used for bacterial growth contains significant amount of redox mediators, such as cysteine, and high strength wastewater contains reduced sulfur species, which can work as abiotic electron donor and increase power production for a short while (Aldrovandi et al., 2009) thus not representing the true performance of the system. This can be avoided by using a minimal salt medium with a single electron donor such as glucose or acetate. To check the influence of wastewater composition on the performance of MFC, Rodrigo et al. (2009) fed MFCs with two different synthetic wastewaters with the same organic pollutants (glucose and peptone) and same organic loading (315 mg/dm^3) but with a different ratio of readily/slowly biodegradable substrate. The MFC fed with slowly biodegradable waste was more efficient in terms of electricity production probably due to the production of intermediates favouring electricity formation.

2.2.2.2 Brewery Wastewater

Wastewater from breweries has been a favorite among researchers as a substrate in MFCs, primarily because of its low strength. Besides, it is suitable for electricity generation in MFCs due to the food-derived nature of the organic matter and the lack of high concentrations of inhibitory substances (for example, ammonia in animal wastewaters) (Feng et al., 2008). Although the concentration of brewery wastewater varies, it is typically in the range of 3000–5000 mg of COD/L which is approximately 10 times more concentrated than domestic wastewater (Vijayaraghavan et al., 2006). It could also be an ideal substrate for MFCs due to its nature of high carbohydrate content and low ammonium nitrogen concentration. Beer brewery wastewater treatment using air cathode MFC was investigated by Feng et al. (2008) and a maximum Power Density (PD) of 528 mW/m^2 was achieved when 50 mM phosphate buffer was added to the wastewater. In this case the maximum power produced by brewery wastewater was lower than that achieved using domestic wastewater, when both wastewaters were compared at similar strengths. This might be due to difference in conductivities of two wastewaters. Diluting the brewery wastewater with deionized water decreased the solution conductivity from 3.23 mS/cm to 0.12 mS/cm. Recently, Wen et al. (2009) using a model based on polarization curve for the MFC, reported that the most important factors which influenced the performance of the MFC with brewery wastewater were reaction kinetic loss and mass transport loss (both were 0.248 V when current density was 1.79 A/m^2). These can be avoided by increasing the concentration of brewery wastewater and by increasing the reaction temperature and using a rough electrode to provide for more reaction sites.

2.2.2.3 Starch processing Wastewater

Starch processing wastewater (SPW) contains a relatively high content of carbohydrates (2300–3500 mg/L), sugars (0.65–1.18%), protein (0.12–0.15%) and starch (1500–2600 mg/L), representing an important energy-rich resource, which can be potentially converted to a wide variety of useful products (Jin et al., 1998). SPW was used as a fuel to enrich a microbial consortium generating electricity and current generation (0.044 mA/cm^2) was coupled toa fall in COD from over 1700 mg/L to 50 mg/L in 6 weeks (Kimet al., 2004). Lu et al. (2009) operated a MFC with SPW containing4900 mg/L of COD over four cycles and obtained a maximum voltage output and power density of 490.8 mV and 239.4 mW/m^2 in the third cycle. However, the CE was only 7%. They attributed this low CE to oxygen diffusion to the anode compartment resulting in oxidization of other electron acceptors, biomass production and fermentation.

2.2.2.4 Dye Wastewater

Azo dyes constitute the largest chemical class of synthetic dyes and are extensively present in effluent from dye-manufacturing industries and textile industries. Their removal from these effluents before discharge is of paramount importance as the intense color of these dyes leads to severe environmental problems such as